Power law model for wind profiles correction in urban environment

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ABSTRACT

Wind speed correction based on the terrain characteristics is commonly found in several wind related applications in the built environment. In some models based on power law profile, the exponent (α) and a correction factor (k) are assumed for each terrain type. This paper aims to check the applicability of one of these models for urban environments with high density. Experiments in a boundary layer wind tunnel were performed for an urban area of 600 x 600 m, in the district of Moema, in the city of São Paulo, Brazil, using a model with 1:500 scale. The test was performed for one predominant wind direction (SE), and the wind profile in the upstream presented exponent of 0.15. The wind profile was measured in 6 points in the scale model using 1D hotwire probe. The predicted profile using the BS5925:1991 method and the measured profiles were compared, and the empirical coefficients (α and k) were recalculated when the results are not in agreement. The recalculated exponent for the area is 0.58, which is much higher than the value prescribed by BS5925 for the "City" terrain type. The wind profile vertical displacement due to the high urban density is not taken into account in the BS5925, but the wind tunnel tests presented values of 60 m for the displacement. The paper concludes that the vertical displacement is the main source of errors in the correction of the wind profile.

1. INTRODUCTION

Wind speed correction based on the terrain characteristics is commonly found in several wind related applications in the built environment.

Using these corrections, one can estimate the wind speed profile in the project site based on a single wind speed measure at the meteorological station.

In this paper, we focus our attention in one popular model for wind speed correction, based on the power law profile.

Due to its simplicity, the power law profile is the most commonly used to describe the vertical variation of wind speed, beside the recognized lack of physical meaning in this approach.

Several state-of-the art building energy simulation (BES) software adopt some kind of power law profile correction for the wind speed, e.g. EnergyPlus (2007), Deru et al (2002), TAS, IES <VE>, IDA ICE, BSim (Wittchen et al, 2004) and ESP-r (Clarke, 2001). Other software dedicated to natural ventilation calculation also adopt power law profiles, e.g. Comis (Feustel et al, 2005), CONTAMW (Walton et al, 2006) and CpCalc+ (Grosso, 1992).

Power law profiles are also used to provide boundary conditions in wind tunnel experiments and CFD simulations, where exponents are associated with typical terrain roughness.

There are a few formulations of the power law corrections, which uses different empirical coefficients. Most of the software cited above adopt the formulation proposed by the British standard BS5925:1991. Based on this fact we adopt the same formulation in this study.

The BS5925 model presents a very simple and straightforward formulation, and classifies the terrain types in 4 groups: open flat country, country with scattered windbreaks, urban and city.

As one can see, only 2 classes describe the urban environment, when the reality shows very complex and heterogeneous urban geometries. Special concern is dedicated to the center of large cities, because the urban density is also high.

Considering those points, this paper aims to check the applicability of the BS5925 model for urban environments with high density.

The lack of validity for this model for urban areas is well known in the wind engineering field. Despite the large number of computational programs using the power law profile in energy and ventilation studies, some might point out the lack of validity of this model.

Full scale experiments are certainly the best option to answer this question, but they are expensive and time consuming. On the other hand wind tunnel experiments are simpler and, even involving several simplifications, can provide some hints about the magnitude of the deviations between theory and practice.

In this research, a small part of the city of São Paulo is modeled in a boundary layer wind tunnel, and the wind profile in the urban environment is measured. The area and the wind tunnel experiment are described in section 2.

Section 3 presents the BS5925 model in detail, focusing on the calculation of the empirical coefficients. Some assumptions implicit on the model could be clarified based on its analysis.

Section 4 presents the comparison of the wind tunnel results and the predictions of the BS5925 model. In most cases they do not agree, so new empirical coefficients are calculated and presented.

Finally, a short discussion about the results is provided followed by the main conclusions of this work.

2. WIND TUNNEL EXPERIMENT

2.1. Area description

The selected study area is part of the district of Moema, in the city of São Paulo. This district is one of the most affected by verticalization and densification in the city.

The area measures 600 x 600 m^2 (Figure 1) and is characterized by a regular grid of streets, and buildings of different heights from 2 to 30 stories, or 6 m to 90 m. The floor area ratio is 2.281 and the occupancy rate is 0.364 for the model area, both on average. The buildings are isolated in each plot, using approximately only half of the plot area.

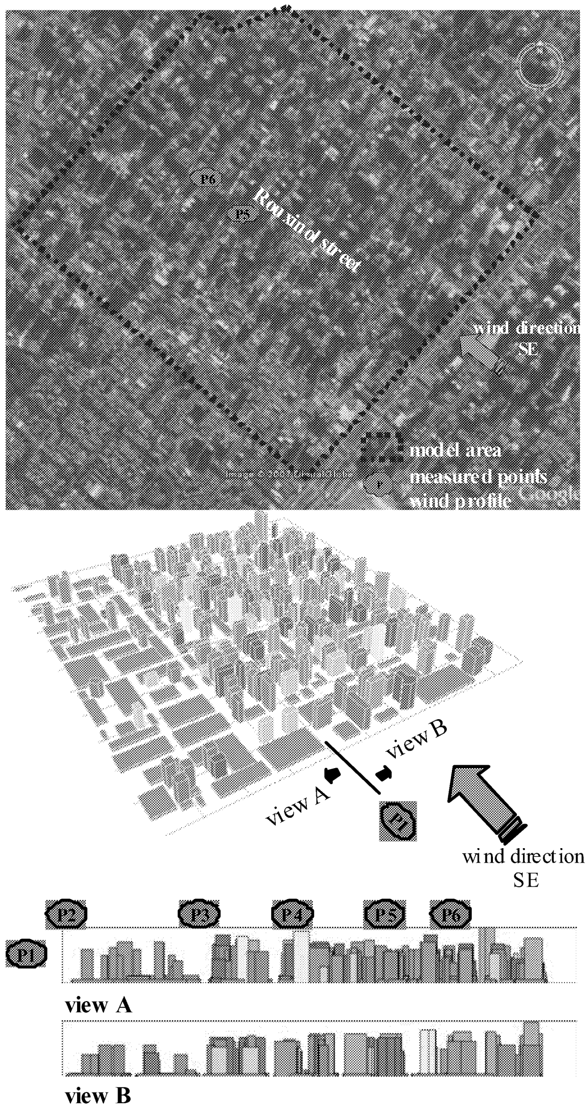

Figure 1: Shows the study area and location point's for measured data.

2.2. Wind tunnel description

The model was built to 1:500 scale, sized 170 x 170 cm^2. This dimension, as well as the selected area, was defined so as to ensure better results in the data gathered from the central part of the model, so only data for the points P5 and P6 are used in this research. The points were in the highest verticalization parts of the chosen area and positioned with greatest proximity between buildings in mind.

The test was performed for one predominant wind direction (SE), and the maximum blockage in the wind tunnel cross section was 2%.

This research used IPT's Atmospheric Boundary Layer Wind Tunnel (Figure 2). The tunnel works in a sub-sonic speed range (up to 30 m/s), low pressure and can generate two types of speed profiles. The test section is 3.00 m wide, 2.00 m tall and 28.00 m long, with a variable-height roof.

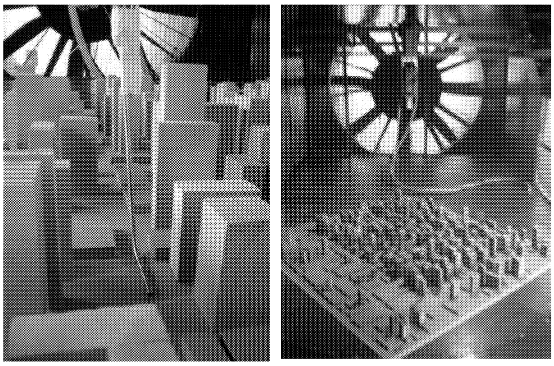

Figure 2: Scale model placed in the wind tunnel

The tests used DANTEC 55p16 hotwire probes, with 10-second measures taken at each height, calibrated with streamline DANTEC internal and external thermometers and barometer.

3. POWER LAW PROFILE - BS5925

This section discusses the formulation presented by BS5925. It intends to isolate the empirical coefficients in the formulas so they can be calculated using the wind tunnel experiments results. The method proposed by the BS5925 consists in the equation 1 and Table 1.

$$U_z = U_{met} \cdot k \cdot z^{\alpha} \quad (1)$$

Where:

U_Z: wind speed at height z AGL – Above Ground Level (m/s)

U_{met}: wind speed at 10 m AGL, measured in the meteorological station (m/s)

k: empirical coefficient define in BS5925

α: empirical exponent define in BS5925

z: above ground level (m)

Table 1. BS5925 empirical coefficients for equation 1

Terrain Type	k	α
Open flat country	0.68	0.17
Country with scattered windbreaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

In order to exemplify the results of equation 1, the corrected profiles for other terrain types are presented in Figure 3, considering U_{met} = 4 m/s. The figure shows that the profile shape is slightly different, and the entire profile is shifted in the lower velocities direction for more rough terrains.

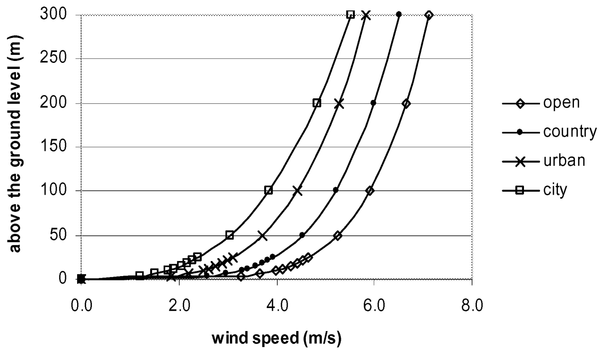

Figure 3. Power law wind profile using the method of BS5925, for U_{met} = 4 m/s

In the following paragraphs the deduction of equation 1 and part of the coefficients in Table 1 is demonstrated. It is necessary to enable the calculation of the new coefficients in cases where the presented method presents discrepancies with the experiments.

The most basic power law profile is presented in equation 2. According to this equation, the profile can be described using only the exponent value. The value of z_r is arbitrary, no matter the chosen one the profile will keep the same shape.

$$\frac{U_z}{U_r} = \left(\frac{z}{z_r}\right)^{\alpha} \quad (2)$$

Where:

U_r: wind speed at the reference AGL (m/s)

z_r: above ground level of U_r (m)

Comparing equations 1 and 2, it is possible to notice that z_r =10 m, and the value of k can be found manipulating equation 2. Let us call the value of k in the meteorological station k_{loc}.

Considering the project site is equal to the meteorological station site, and so applying equation 3 to the open flat country terrain in Table 1 the k value can be calculated because K = k.

$$\frac{U_z}{U_{10}} = \left(\frac{z}{10}\right)^{\alpha}$$

$$\frac{U_z}{U_{10}} = \frac{z^{\alpha}}{10^{\alpha}}$$

$$U_z = U_{10} \cdot \frac{1}{10^{\alpha}} \cdot z^{\alpha}$$

$$U_z = U_{10} \cdot K \cdot z^{\alpha} \quad (2.1)$$

So,

$$K = \frac{1}{10^{\alpha}} \quad (3)$$

Where:

U_{10}: wind speed at 10 m AGL, measured in the project site (m/s)

K: empirical coefficient

The same cannot be said of the other terrain, because the profile in equation 2 is not made to transpose values, but to describe the wind profile based on an exponent and wind measurements at some reference height.

It is possible to reconstruct the k values on Table 1 based on the K value calculated in equation 3 from the profiles in Figure 3. It is made by comparing equations 1 and 2.1, and making both equal to:

$$\frac{U_z}{z^{\alpha}}$$

So,

$$\frac{k}{K} = \frac{U_{10}}{U_{met}}$$

$$k = K \cdot \frac{U_{10}}{U_{met}} \quad (4)$$

Equation 4 shows that the k value for the wind profile correction is nothing more than the original profile K value weighted by the ratio between the speed in the site and the speed in the meteorological station. In equation 4, U_{10} could be any other AGL. In fact, depending on the above ground level used to calculate this ratio the k value obtained is different, because the relation between the two speeds is not completely linear. In this sense, the choice of any above ground level is arbitrary, and the assumption of linearity is a simplification in this approach. AGL = 10 m gives the best results to reproduced k values found in Table 1. The ratios adopted are presented in Table 2.

Table 2. Empirical coefficients for equation 4, based on equation 4

Terrain Type	U_{met}/U_{10}
Country with scattered windbreaks	0.82
Urban	0.62
City	0.45

4. RESULTS

Figure 4 presents the measured profiles in their respective positions in the model cross section.

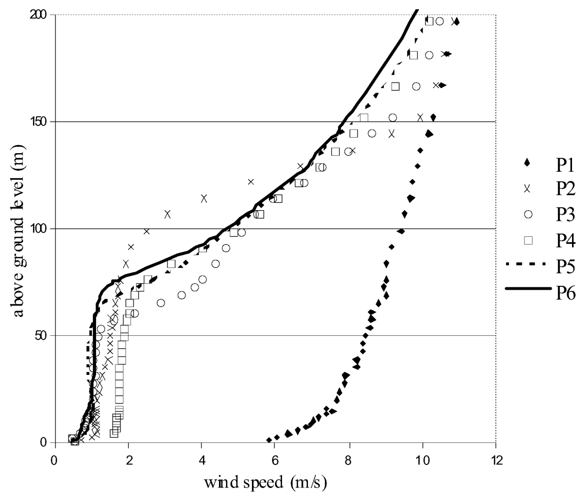

Figure 4: Wind tunnel mean wind speed profile

As expected the profile changes significantly in the new terrain. The points near the front border show a more complex profile, while those at the end of the model are more clear and defined. In all profiles, the displacement of the profile base from the floor can be clearly noticed. In order to allow a better comparison among the profiles, presents them in a single chart.

Figure 5 different profiles for the point P5, and point P1 fitted curve is shown as reference. The dots show the measured profile, while the thin line presents the predicted profile according to BS5925 considering the urban. It is clear that the profiles do not have any similarities. The displacement from the ground is not represented, nor the curve slope. The dashed line shows a fitted curve which presents good agreement with the measured data.

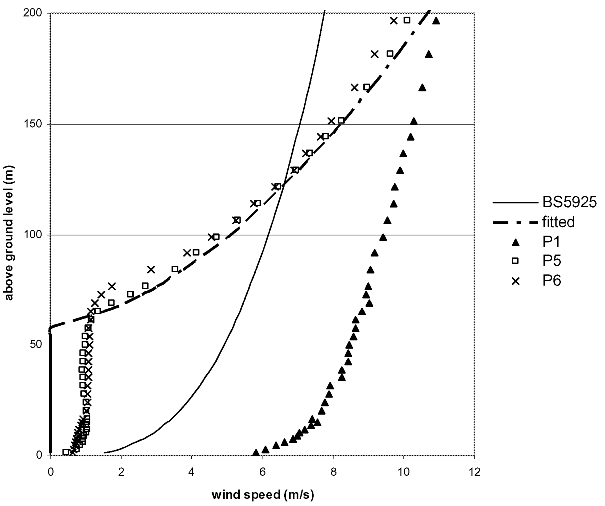

Figure 5: Wind tunnel mean wind speed profile – P1 and P5

Table 3 brings the parameters used in the fitted curve presented in Figure 5. In order to represent the profile displacement from the floor, a new equation is proposed.

Table 3 . BS5925 empirical coefficients for equation 1

Terrain Type	k	α	z_d
Direction (SE) – point P1	0,58	0,20	0
Direction (SE) – point P5	0,09	0,58	60
Direction (SE) – point P6	0,09	0,58	60

5. DISCUSSION

The uncertainty in the measurement plays an important role in the results analysis. In the present case, the uncertainty in the probe position is estimated to be 2 mm, which corresponds to 1 m in the full scale profiles presented in the previous section. This uncertainty is based on the probe size, and the characteristics of the mechanical position system used to locate the probe in the test section. Considering the magnitude of z_d values found, the present uncertainty is not reason for concern.

The vertical displacement is clearly the weak point in the formulation presented by BS5925.

The power law can only characterize the profile above z_d level, but this fact is not explicitly shown in the present formulation.

Clarke (2001) recommends care on applying wind profiles models in the urban context, but he also points that the buildings in this context are those which could really benefit from ventilation studies. In the software ESP-r, this dilemma is clearly presented when logarithm models are used. In this case, the software interface informs the user that the modeled building height cannot be smaller than the surrounding building height.

Based on this brief discussion, we conclude that the formulation below could better describe the limitations of the BS5925 model.

$$U_z = U_{met} \cdot k \cdot (z - z_d)^{\alpha} \qquad (5)$$

This formulation requires knowledge about z_d. Allard (1998) suggests that a first approximation can be obtained based on the averaged obstacle height (h_0), where:

$$z_d = (0.7) \,.\, h_0 \qquad (6)$$

In the present experiment z_d and h_0 have approximately the same value, which is 50 % higher then the value suggested by Allard (1998).

Despite the difficulties to evaluate zd based on the urban geometry, Equation 5 merit is to put in the same level of importance the vertical displacement and the terrain roughness. The present formulation of the BS5925 model reflects the common opinion that the terrain roughness is the main parameter to describe wind profile modifications.

One possible reason for this wrong assumption may come from meteorological models. Research on meteorology was always an important source for wind engineering and ventilation research. In medium and large scale meteorological models, z_d is not a relevant variable facing the magnitude of the problem.

The systematic use of z_d will certainly impact the revision of current practices of wind tunnel and CFD simulations, in order to include this parameter in the boundary conditions definition.

The use of z_d also demands alternative definitions for parameters like the pressure coefficients, for instance. Pressure coefficients usually adopt the wind speed at the building height as reference. If this height is equal or smaller than z_d, the present definition is meaningless.

In this sense, it might be argued that the paper brings no new contribution, which is - in fact - true. However, practice shows that the topic is far from consensus in the building energy and ventilation community. A large number of software adopts this wind profile correction without warning the user about its validity. z_d is also not mentioned in important handbooks such as ASHRAE (2005) and CIBSE (1999). The BS5925 description for the terrains also contributes to occasional misuse, when describing terrains like "Urban" or "City", which are by nature dense, and where the profile correction is probably not valid.

The study of urban areas with high density presents several challenges, and the present paper intends only to highlight some contradictions in the current modeling methods.

6. CONCLUSIONS

Based on wind tunnel experiments, is it demonstrated that the present formulation of the power law model in the BS5925 does not work in an urban environment with high density.

The present case study shows a vertical displacement in the wind profile of 60 m, and the exponent of 0.58 which is much higher than the value suggested by the standard.

The study indicates that the inclusion of a new term in the model is necessary to represent the vertical displacement.

7. ACKNOWLEDGEMENTS

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